Binaural Auditory Processing Among Middle-Aged Adults

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ABSTRACT

Binaural listening, or listening with both ears, allows a listener to better localize and understand speech than with one ear alone. For some aging adults, however, this binaural advantage does not exist, or is reduced relative to normal for speech-in-noise tasks. In addition, some older adults tend to exhibit an exaggerated right ear-advantage (REA), or better recognition of signals presented to the right ear than the left during dichotic listening tasks, compared to young adults (i.e., Noffsinger et al., 1996). There is limited research, however, exploring if these age-related changes in binaural listening begin to be demonstrated in mid-life. The present study examined binaural versus monaural processing for 30 middle-aged adults (ages 31-59 years) possessing no more than a mild high-frequency sensorineural hearing loss. Two types of word recognition assessments were implemented: (1) word recognition in noise and (2) dichotic word recognition. For the word recognition in noise tasks, subjects responded under three conditions: (1) monaural left ear, (2) monaural right ear, and (3) binaural. For the dichotic listening tasks, subjects responded in: (1) free recall, (2) directed-recall right, and (3) directed-recall left. Results were compared to previously-collected data for 30 young adults (ages 18-30 years) and 30 older adults (ages 60-89 years). Overall, middle-aged adults performed slightly poorer than young adults but showed performance patterns more similar to young than older adults. In sum, these results suggest that age-related binaural auditory processing deficits may not present in middle age. Results do suggest, however, that individual variability exists within this age group and that individual performance patterns should be considered when making conclusions about binaural auditory processing in middle age. The present study supports future research regarding age-related changes in the auditory system across the adult lifespan.

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CHAPTER 1

INTRODUCTION

Human beings are designed to use two ears to perceive sound, and there are certain advantages associated with using two ears to listen, termed binaural listening, rather than solely one ear. These binaural advantages include: (1) better localization ability, (2) binaural summation, and (3) binaural squelch. Due to the fact that the two ears are located on directly opposite sides of the human head, there are two locations for sound to enter the auditory system. The sound wave information (i.e., timing, intensity of the sound wave to each ear) can then be compared across these two separate locations. Because sound waves will differ in timing and intensity across ears, these differences serve as instrumental cues in locating the source of a sound. Sounds arrive at one ear before the other, leading to what are known as interaural time differences. Sounds are also attenuated as they travel from one place to another; therefore, a sound reaching the right ear after the left ear will be less intense because it travels a greater distance and is diffracted (or “shadowed”) by the head. Localization ability is reliant on location of the sound source and interaural time and level differences between the two ears (Akeroyd, 2006; Yost, 2007, p.173).

When listening with two ears, we also experience a “summation effect,” in which we perceive sound as being louder than when listening with one ear alone (Reynolds &

Stevens, 1960). Binaural summation of loudness depends both on the level and frequency of the stimulus (Porsolt & Irwin, 1967) and has been shown to range from 3 dB at threshold levels to as high as 10 dB at suprathreshold levels (Hirsh, 1948; Mencher & Davis, 2006). When receiving similar input from the right and left ears, the central auditory system is considered to act on this input in an additive manner, resulting in an improvement in perception of the respective signal. Listeners likewise report a reduction in listening effort required when listening with two ears as opposed to one (Brooks, 1984).

Additionally, binaural listening provides us with a greater ability to understand a desired speech signal in competitive listening environments, termed binaural squelch (Gelfand & Hochberg, 1976; Yost, 2007, p. 185). As Byrne (1981) elaborates, when both ears are processing a speech signal in the presence of a competing signal and the signal and noise are at different locations, time and level differences between the ears occur. The auditory system can act on these time and level differences, segregate the signal from the undesired noise, and essentially ignore at least a small portion of this noise. Binaural squelch is therefore a phenomenon that relies on an efficient central auditory system.

The binaural advantages outlined above are not entirely universal, however. Some individuals, notably older adults with sensorineural hearing loss, may have more difficulty comparing auditory time and level differences across the two ears to effectively localize and understand sound. Research shows that declines in localization ability can actually be apparent as early as the third decade of life and continue to decline throughout middle and older age, attributable to central auditory function decline (Dobreva et al., 2011; Abel et al., 2000).

Moreover, there is evidence to suggest that, for some people, listening to speech binaurally can actually be disadvantageous, especially in noisy situations. For example, research has indicated that some older adults with sensorineural hearing loss exhibit greater benefit when listening with one ear rather than both ears in competitive listening situations (Dubno et al., 2008; Jerger et al., 1993). These deficits in binaural processing are considered to reflect dysfunction in “higher” auditory centers (i.e., the central auditory system), and research points to aging as a possible factor for affected older listeners (Bellis & Wilber, 2001; Dubno et al., 2008). Some older adults exhibit an auditory phenomenon in which the performance of the better ear is in fact impaired by performance of the poorer ear. Termed binaural interference (Jerger et al., 1993), it is estimated that approximately 8 to 10 percent of older adult hearing aid users experience this phenomenon. In terms of rehabilitation, those experiencing binaural interference may find greater benefit from monaural amplification and/or use of an FM system rather than a traditional binaural hearing aid fitting, despite symmetrical pure-tone thresholds (Carter et al., 2001; Chmiel et al., 1997; Walden, 2006).

In order to examine binaural processing, difficult test measures must be used to tax central auditory areas. Two types of measures commonly implemented are speech-recognition in noise and dichotic speech tasks. Speech recognition in noise tasks require a subject to identify a speech stimulus in the presence of a background competitor (i.e., multitalker babble, which is comprised of multiple speakers simultaneously emitting non-meaningful speech). A variety of speech materials can be used (numerical digits, words, or sentences), but monosyllabic words seem to produce the best results in terms of delineating normal from abnormal performance (Wilson, 2003). Word recognition in noise tasks can be tested in the right and left ears separately (monaural condition) or both ears at the same time (binaural diotic condition).

Dichotic listening tasks entail presenting *different* signals to each ear simultaneously: a stimulus to the left ear and a different stimulus to the right ear. For the majority of listeners, speech signals presented to the right ear are recognized more accurately than signals presented to the left ear (Kimura, 1967). This phenomenon is known as the right ear-advantage (REA), and REAs for older adults are often larger than those exhibited by young adults. Often, this large REA, or a large left-ear disadvantage (Jerger et al., 1994), may be indicative of aging and decreased integrity of the corpus callosum and the central auditory system (Bellis & Wilber, 2001). Ear advantages are often not detected via traditional audiologic clinical testing, however, and can exist in the presence of symmetrical peripheral hearing thresholds and speech recognition abilities in quiet (Jerger, 2001).

Most research in the area of binaural auditory processing and aging focuses on the geriatric population. Young adult listeners (18-30 years) with normal hearing are usually used as a control group. There are limited data, however, regarding the binaural auditory processing abilities of middle-aged adults (31-59 years) and if aging effects on the auditory system are exhibited earlier in life than previously believed. Bellis and Wilber (2001) showed that decreased interhemispheric transfer of auditory information, a likely contributor to binaural auditory processing deficits due to aging, starts to degrade in middle adulthood (40 to 55 years). More recently, studies have focused on speech perception in difficult listening environments (higher auditory processing) for middle-aged adults. These studies suggest that, despite normal or near-normal hearing, middle-aged adults tend to show a subtle reduction in auditory perceptual skills, such as dichotic listening and speech perception in noise (Helfer & Vargo, 2009; Leigh-Paffenroth & Elangovan, 2011). Although these studies reveal reduced temporal processing and speech perception in complex listening environments for middle-aged adults compared to young adults, there have been no specific comparisons made between monaural and binaural performance in noise and dichotic listening task performance for middle-aged adults.

If binaural processing deficits are indeed associated with biological changes due to aging, at what point in the human lifespan does this begin to affect performance, and is it earlier than previously reported? The results of the present study may therefore prove to be significant in several ways: (1) the comparison of binaural processing abilities of middle-aged adults to those of older and young adults for two types of complex listening tasks; (2) for clinical applications, by suggesting whether or not certain audiologic assessment/rehabilitation strategies (i.e., hearing aid fitting strategies or auditory training techniques) may be a significant consideration for presenescent adults; and (3) for research applications, by supporting past research and stimulating future research related to the aging auditory system across the adult lifespan.

The present study explored two main questions: (1) What is the relationship between dichotic listening and left-ear, right-ear, and diotic binaural word recognition in noise among middle age adults (31-59 years)?; and (2) How does recognition performance compare to normal hearing young adults (18-30 years) and older adults with hearing loss (60-89 years)?

Based on past research, it was expected that, on average, subjects would exhibit a REA for the dichotic listening tasks during the free-recall response condition, but that the older adult subjects would exhibit a more exaggerated REA than the young and middle-aged adult subjects and that the middle-aged subjects would display a larger REA than the young adult subjects. It was also anticipated that the young adults would demonstrate the best overall performance for the word recognition in noise tasks and that the middle-aged subjects would perform better than the older adult subjects for the word recognition in noise tasks, but all subjects would exhibit poorer performances as the signal-to-noise ratio (SNR) is decreased. Moreover, it was hypothesized that the older adult age group would display the greatest amount of intersubject variability and that the middle-aged adult group would show greater intersubject variability than the young adult age group.

CHAPTER 2

BACKGROUND & LITERATURE REVIEW

The Binaural Advantage

There is a substantial amount of research supporting distinct advantages when using two ears to process sound as opposed to one ear. Binaural processing, or the effective use of information from both the right and left ears, relies on the integrity of both peripheral and central auditory systems. In normal binaural processing, the central auditory system can compare inputs from both peripheral systems and integrate this information, resulting in improvements in several components of listening (Gatehouse & Akeroyd, 2006).

Better localization of the sound source is achieved with the use of two ears as opposed to one. The location of human ears on directly opposite sides of the head allows for a comparison of sound information (i.e., timing and intensity of the sound wave to each ear) across these two separate locations. Sound waves will thus differ in these aspects of timing and intensity across ears, and these differences act as instrumental cues in sound source location. Sound arrives at one ear before the other, leading to ITDs. Sound is also attenuated as it travels from one place to another; therefore, a sound reaching the right ear after the left ear will be less intense because it travels a greater distance and is attenuated (or “shadowed”) by the head, leading to IIDs.

Localization ability in the horizontal plane is reliant on location of the sound source and ITDs and IIDs between our two ears (Akeroyd, 2006; Middlebrooks & Green, 1991). The ability to localize sounds is notably important in competitive listening environments, such as background noise. For most listeners, spatial differences between the two ears allow for discrete temporal and distance cues for each ear (Grose, 1996). The listener can then process these separate cues and spatially localize each component or signal within the background noise. As a result, a listener with normal binaural processing can more easily discriminate the meaningful message from the unwanted noise (Dubno et al., 2008). Thus, the difference in the interaction of sound between our two ears and our central auditory system's effective comparison of these differences is imperative for our localization of sound in the horizontal plane. Monaural listening does not result in this same advantage in noisy/reverberant environments due to the lack of comparison at the central auditory level between the two peripheral systems.

Another advantage of binaural listening is an increase in the perception of loudness of a sound when compared to listening to the same sound with one ear alone. Termed the summation effect, this advantage has been exhibited to be dependent upon the level of the stimulus (Hirsh, 1948; Mencher & Davis, 2006). Binaural summation of loudness has been attributed to the additivity that the central auditory system enacts when receiving the same input from both peripheral sources. The redundancy of both inputs results in improved perception, which exists in different degrees from threshold to suprathreshold levels. Although there are many studies to describe this phenomenon behaviorally, the exact anatomic/physiologic mechanism behind binaural summation is still not well understood. Lesion studies by Calearo (1957) indicate that both temporal lobes must be intact for normal binaural loudness summation to occur. It seems, then, that the mechanism responsible for binaural summation of loudness must rely at least in part on the integrity of both cortical areas of the auditory system as well as the peripheral auditory system.

The Aging Auditory System: Binaural Listening and Binaural Interference

There are many changes associated with aging throughout the body, but how is the auditory system affected by aging and how does this impact the ability to use binaural information? We know that some of the most common complaints among older adults involve understanding speech in competitive listening situations. Much of the research related to geriatric audiology involves bettering our understanding of the aging auditory system at both the peripheral and central levels. In their study of age-related changes in speech recognition, Kim and colleagues (2006) found age-related differences in performance for binaural recognition in both quiet and noise. All of the subjects in this study had clinically-normal hearing (pure-tone thresholds of 25 dB HL or better at 250- 8000 Hz), yet there were significant differences found between older adults and their middle-aged and young adult counterparts. The older adults with normal hearing performed significantly worse than middle-aged and young adults with normal hearing in speech understanding tasks. These differences were significant for both quiet and noisy conditions, which was an unexpected finding. As the authors suggest, these differences in the absence of peripheral hearing loss suggest that at least part of the issues related to older adults' complaints of decreased speech understanding relates to changes beyond the peripheral auditory system.

In their 1978 study, Warren and colleagues concluded that elderly subjects with high-frequency hearing loss have significantly more difficulty than young adults in recognizing speech in background noise. They found that this difference was more pronounced in a dichotic condition (different signals to each ear in that interaural directional cues were preserved) compared to a diotic condition (same signal to both ears with no interaural differences). The older adults, then, did not derive the same benefit as their young adult counterparts from directional cues inherent in the dichotic stimuli to assist in localizing and separating the speech signal from the noise. Based on their results, Warren and colleagues suggest that, as the auditory system ages, it becomes less efficient in separating speech signals from noise, or binaural signal analysis.

Many studies indeed show that older adults demonstrate a different overall pattern in performance for dichotic listening tasks (i.e., Drachman et al., 1981; Jerger & Jordan, 1982; Noffsinger et al., 1996). Specifically, this research shows that older adults tend to exhibit lower correct recognition performance for dichotic stimuli and a stronger preference for materials presented to the right ear, or a REA. Although the aging auditory system is a factor in these changes in performance for dichotic stimuli, the effects of peripheral hearing loss are often hard to separate among older age groups. Studies using normal and near-normal hearing older adults (i.e., Kurdziel & Noffsinger, 1977), however, confirm that age in addition to hearing loss is an important consideration for processing of dichotic stimuli.

For some older adults, binaural listening can actually be disadvantageous. This is particularly true in competitive listening situations where another sound source competes with the signal of interest. When the performance of the better ear is actually impaired by performance of the poorer ear in speech recognition tasks, the individual is said to experience binaural interference (Jerger et al., 1994). This auditory phenomenon has been estimated to exist in as many as 8 to 10 percent of hearing aid users in the older adult (60 years of age and older) population (Jerger et al., 1993). Using aided speech recognition and middle-latency evoked potentials, Jerger and colleagues investigated binaural interference in four older adults with symmetrical peripheral pure-tone thresholds. Jerger et al. found that performance was better in the monaural condition compared to the binaural condition for both the behavioral and electrophysiological tasks. These findings exemplify that, for these individuals, there is no binaural advantage, only a binaural *disadvantage*.

A substantial body of research reaffirms the work of Jerger et al. (1993), suggesting that older adults experiencing a binaural deficit may obtain more benefit from listening with one ear than with both ears. For example, in a 1997 article, Chmiel et al. relate a case study of a 90-year old woman. Although she possessed symmetrical pure-tone thresholds, this individual was found to perform best when aided monaurally in the right ear only than when binaurally aided or monaurally aided in the left ear.

Allen et al. (2000) conducted a study to explore the prevalence of binaural interference among young adults with normal hearing and older adults with normal hearing and with hearing loss. According to the findings of this study, the prevalence of binaural interference in the older adult population is near what would be predicted by statistical chance: 2 of the 12 older, hearing-impaired subjects in this study exhibited binaural interference in speech recognition testing under diotic conditions, despite having symmetrical hearing losses. The researchers conclude that the true prevalence of binaural interference among older adults could possibly be close to the 8 to 10 percent prevalence estimated by Jerger et al. (1993).

Carter and colleagues (2001) examined performance patterns of four listeners who reported little benefit with binaural amplification and preferred monaural amplification despite having symmetrical hearing loss. These subjects did not show an advantage from being aided binaurally compared to the unaided condition in speech recognition tasks. In fact, these individuals exhibited greater benefits for speech recognition in the presence of noise when fit monaurally with a hearing aid and/or when using an FM system than when fit binaurally with hearing aids.

In a study conducted by Walden and Walden (2005), a sample of adults ages 50 to 90 years old with symmetrical sensorineural hearing loss showed better speech recognition in noise performance (using the Quick Speech-in-Noise Test, or QSIN) when unilaterally aided than when bilaterally aided. In addition, the researchers compared each subject’s performance on the dichotic digits test and compared this to monaural

QSIN performance; they found that the better-performing ear on the dichotic digits test tended be the ear having lower SNR loss, or better performance, on the QSIN. The researchers offer that, even though the majority of individuals with bilateral hearing loss will benefit with bilateral amplification, older adults may perform better when removing one hearing aid in difficult listening situations (i.e., speech in background noise).

According to many researchers, this benefit profile (better performance with unilateral amplification in difficult listening situations despite symmetrical hearing loss) could be best explained by central auditory processing decline related to decreased interhemispheric transfer integrity in the brain. Specifically, the corpus callosum, the fiber tracts connecting the two hemispheres of the brain, has been suggested to undergo age-related atrophy in myelination (Janowsky et al., 1996). This change in myelination can result in less effective transfer of information between the two hemispheres of the brain, interfering with many everyday tasks and behaviors, such as those involving attention, memory, binaural auditory processing, and visuospatial processing (Bellis & Wilber, 2001). As proposed by Kimura (1961) and supported by later studies (i.e., Aiello et al., 1995; Hugdahl et al., 1999; Musiek et al., 1980), when competing stimuli are presented to the two ears, transfer of ascending auditory information is stronger along contralateral than ipsilateral pathways. Because most individuals are left hemisphere dominant for language perception, a signal presented to the left ear must travel to the right hemisphere and then cross via the corpus callosum to be perceived in the left hemisphere. In contrast, a signal presented to the right ear under this model ascends directly to the left hemisphere and will not need to crossover via the corpus callosum. If the integrity of the corpus callosum is compromised, an individual will therefore show an exaggerated preference for signals presented to the right ear (i.e., REA) due to this more direct pathway for recognition of speech. In the cases of binaural interference and exaggerated ear advantages/ear disadvantages (i.e., Jerger et al., 1993; Chmiel et al., 1997; Allen et al., 2000), it is argued that these individuals experience compromised interhemispheric transfer of information and that the main structure corresponding to this age-related change may be the corpus callosum.

Binaural Processing in Middle Age

The term “age-related changes” is non-specific, which leads us to question when in the average adult lifespan we should expect the occurrence of these changes in the integrity of the auditory system due to the aging process. A review of the literature on age-related changes in the auditory system reveals that the majority of studies focus on older adults – typically those ages 60 years and older – and often compare these results to young adults with normal hearing. Significantly less is known about middle age adults and if age-related changes begin at this period of life, and if so, how these might affect the binaural processing of adults in mid-life.

In their investigation regarding age and gender effects on interhemispheric function, Bellis and Wilber (2001) found that, for dichotic listening and an auditory temporal patterning task (humming-labeling differential), interhemispheric transfer integrity (measured as transfer time) begins to decline earlier in human adulthood than "old age". Their study suggests that this decline begins between the ages of 40 to 55 years and tends to stabilize thereafter. Based on these findings, the researchers assert that this decline in interhemispheric integrity could contribute to the common complaints of decreased speech understanding in difficult listening situations and other problems associated with age-related decreased binaural processing.

Several studies have focused on speech perception in difficult listening environments (higher auditory processing) for middle-aged adults. A number of these studies suggest that, despite normal or near-normal hearing sensitivity, middle-aged adults tend to show a subtle reduction in certain auditory perceptual skills, such as dichotic listening and speech perception in noise (Barr & Giambra, 1990; Helfer & Vargo, 2009; Leigh-Paffenroth & Elangovan, 2011). For example, Kim et al. (2006) revealed an age effect when comparing young adults and middle-aged adults with normal hearing on speech recognition in noise performance. Specifically, overall performance and the binaural advantage for sentence perception in noise were significantly reduced in middle-aged adults versus young adults. When examining speech recognition ability in quiet, however, middle-aged adult performance was similar to young adults. This finding from Kim and colleagues provides some support for the idea that age-related changes in more central portions of the auditory system may begin to present behaviorally in middle age.

With the use of cortical auditory-evoked responses, Ross and colleagues (2007) provide electrophysiological evidence that age-related changes of portions of the central auditory system important for binaural auditory processing appear to begin at or before mid-life. As the authors point out, binaural hearing relies on the perception and comparison of certain physical properties of sounds (i.e., time, intensity cues). In this study, magnetoencephalography (MEG) was used to measure subjects' cortical responses to changes in interaural phase differences for amplitude-modulated tones. Because performance on this task relies on input from both ears, it is an effective way to gauge central auditory processing for binaural information. Results from young, middle-aged (ages 45-55 years), and older adults (ages 65-79 years) were compared. Hearing was within normal limits for the young and middle-aged adults. Significant age-related declines for this measure were found, indicated by reduced frequency range in detecting interaural phase differences, and this was found to be significantly reduced among the middle-aged adults compared to the young adult group. Further changes in cortical responses occurred in the older adults, but large intersubject variability in this group suggests that this process is certainly not uniform. Though this study suggests that the onset of age-related changes in binaural hearing may begin in mid-life, there is no predictable pattern to discern the degree of decline that may occur by older adulthood.

A study by Helfer and Vargo (2009) revealed reduced speech recognition in the presence of background noise for middle-aged women (ages 45-54 years), even though the subjects possessed normal pure-tone thresholds (from 250-4000 Hz). The middle-aged women were compared to a control group of young adult women with normal hearing. A significant difference in performance was found between these two groups on a sentence recognition task in the most difficult listening condition of the experiment (where a speech masker was implemented and not spatially separated from the target). Although some of the middle-aged subjects possessed a hearing loss at frequencies above 4000 Hz, performance on this particular task was not correlated with hearing thresholds. There was, however, a significant correlation found between this speech recognition task and performance on the Gaps-in-Noise (GIN) Test. Additionally, the middle-aged subjects reported significantly greater difficulty in their perceived ability to understand speech in difficult listening situations compared to young adults, despite having normal to near-normal hearing thresholds. These findings suggest that there are subtle, yet significant, changes that occur in middle age that affect auditory processing and that middle-aged adults perceive these greater difficulties, at least in the most challenging listening situations. The authors do point out, however, that high-frequency hearing loss (even of a mild degree), may act in conjunction with more central auditory changes to affect speech recognition in background noise.

Similarly, Leigh-Paffenroth and Elangovan (2011) showed decreased word recognition performance in noise for middle-aged subjects (ages 40-55 years) with and without mild high-frequency sensorineural hearing loss compared to normal hearing young adults. These results support the findings from Helfer and Vargo (2009), proposing that there are age-related effects of auditory processing that begin to present in middle age. The findings from Leigh-Paffenroth and Elangovan (2011) and Helfer and Vargo (2009) suggest that high-frequency hearing loss of even a mild degree (something that is becoming increasingly more common in younger age groups [Agrawal et al., 2008]), may be a co-contributor to age-related decline in speech recognition in noise. Nevertheless, by examining middle-aged adults with normal hearing and high-frequency hearing loss and showing that both groups showed significantly poorer performance in noise than young adults, Leigh-Paffenroth and Elangovan provide evidence for changes in higher auditory channels occurring in middle age.

Recently, Davis et al. (2013) examined interaural asymmetry in dichotic listening tasks. Using a quasi-dichotic listening paradigm and measuring the N400 response of the auditory-evoked potential waveform, data were collected from young adults and middle-aged (ages 44-57 years) female participants with normal hearing. Results showed that the N400 response was greater for the middle-aged group when competing speech was directed to the right ear than when directed to the left ear, suggesting middle-aged women exhibit a slightly-enhanced left-ear deficit (LED) in competitive listening situations, even with normal hearing acuity, as compared to young adults. The researchers purport that, although this interaural asymmetry difference is not as exaggerated as when comparing young adults to older adults (ages 60-90 years), it does suggest that age-related changes to binaural hearing may begin to affect individuals in mid-age. The authors further advocate for the continued recruitment of middle-aged adult listeners in studying age-related changes in the auditory system.

Although the above studies are intriguing in that they reveal reduced speech perception for middle-aged adults compared to young adults in more difficult listening environments, there are still many questions remaining. Of note, there is a lack of research that focuses on comparing binaural versus monaural processing of speech in competing signals. Namely, there are no specific comparisons made between behavioral measures of monaural and binaural speech recognition in noise and dichotic listening task performance for middle-aged adults. As Martin and Cranford (1991) point out, electrophysiological data and behavioral data in this area of research may reflect different underlying changes to neural networks. More is needed in both arenas of research in order to better understand age-related changes to binaural processing.

Speech Recognition Tasks to Assess Binaural Processing

Current standard clinical audiologic testing (i.e., pure-tone threshold testing and speech recognition measures in quiet) does not effectively assess the integrity of the central auditory system. More challenging tasks, such as the use of competing or degraded signals, are needed in order to “tax” the auditory system and reveal information about higher auditory centers. In difficult listening environments, the listener is forced to compare information of greater complexity between the two ears compared to the information contained in quiet listening environments. This comparison cannot be made at the peripheral level. It is at the level of the superior olivary complex (SOC) and beyond that the auditory system uses binaural information (Eldredge & Miller, 1971). Effective use of information from both ears, called binaural fusion, is necessary for understanding speech in the presence of competing signals and is an important role of the SOC and higher auditory processing centers (lateral lemniscus, inferior colliculus, medial geniculate body, auditory cortex).

There are various behavioral methods to examine binaural processing abilities. Two types of speech measures commonly used are speech recognition in noise and dichotic listening. A dichotic listening task involves presenting two different signals to each ear simultaneously and then asking the subject to repeat the signal(s) of interest, which may include the stimulus perceived in one ear only or both of the stimuli perceived in the right and left ears. Speech recognition in noise tasks, on the other hand, are typically presented diotically, meaning the same stimulus is delivered to both ears simultaneously. Speech recognition in noise measures can also be conducted monaurally, testing each ear alone.

Speech recognition in noise tasks require the listener to identify a stimulus in the presence of a competing signal. There are various competing signals that can be implemented, including white noise, speech-shaped noise, or a single-speaker masker. A competitor mimicking “everyday” background noise and often implemented in these tasks is multitalker babble (MTB), which is comprised of multiple speakers simultaneously emitting non-meaningful speech. Speech-recognition tasks can use numerical digits, nonsense syllables, words, or sentences as stimuli. These stimuli vary in their linguistic meaning and difficulty. For the purposes of testing auditory perception, monosyllabic words are an effective stimulus to implement by being neither too difficult (like nonsense syllables) nor too easy, like the contextual information offered by sentences or the closed-set nature of digits (Wilson & Jaffe, 2003).

There are several factors to consider when conducting word recognition in noise testing. As previously mentioned, word recognition in noise tasks can be tested in the right and left ears separately (monaural condition) or both ears at the same time (binaural diotic condition). When considering the binaural advantage, most individuals should demonstrate better performance in the binaural condition compared to either monaural condition, though Wilson and Jaffe (2003) deduce that this advantage is decreased for word recognition in noise tasks. The age of the participants should also be considered. As with most higher-auditory tasks, young adults tend to exhibit better recognition scores for words in noise tasks compared to older adults with and without hearing loss (i.e., Warren et al., 1978). More recently, Helfer and Vargo (2009) reported that middle aged adults, on average, also perform poorer than young adults for speech recognition in noise measures and that this difference increases as the task difficulty increases.

Considerations in Dichotic Listening Testing

Ear Advantage

Using a dichotic listening paradigm to explore language lateralization, Kimura (1961) described a common performance pattern: more accurate recognition of a verbal stimulus presented to the right ear than a competing stimulus presented to the left ear. This phenomenon has been termed the REA and has been shown to exist in the majority of individuals. Language is typically lateralized in the left hemisphere, and because contralateral pathways are the primary pathway for ascending auditory information and the ipsilateral pathways are mostly suppressed during dichotic listening, a signal arriving at the right ear will be directly transferred to the left hemisphere. In contrast, a signal arriving to the left ear will first be transmitted to the right hemisphere and must then cross over (via the corpus callosum) to the left hemisphere before being recognized. Consequently, there is a greater path required for recognition for signals presented to the left ear for most individuals. This is behaviorally exhibited as a slight REA in dichotic listening studies for the majority of people (Bryden, 1988).

Age Effects

Age effects on dichotic listening have been reported, often attributed to degradation of interhemispheric transfer integrity – specifically, the corpus callosum. A more pronounced REA, sometimes described as a left-ear disadvantage, is often exhibited by older adults and is considered to be indicative of these age-related changes in the central auditory system. Indeed, Bellis and Wilber (2001) report older subjects exhibit exaggerated REAs when compared to their normal-hearing counterparts, who tend to exhibit only slight REAs. Bellis and Wilber contend that age-related changes to interhemispheric transfer integrity begin to appear in middle age - between the ages of 40 and 55 years - but appear to reach a “plateau” and do not continue to markedly decline after this period of life. There is sparse research, however, examining the degree of REA in behavioral tasks (i.e., dichotic listening) among middle-aged adults compared to performance on the same tasks by young and older adults.

In a comprehensive review by Grose (1996), several studies are examined that relate to binaural processing of the aging auditory system. Grose argues that there exists a “spectrum of binaural tasks,” where each task is ordered relative to the degree of binaural processing it requires. Localization of sound, for example, is labeled as a “lower level” task and dichotic speech recognition is rated as a “higher level” task. Jerger and Jordan (1992) examined performances of older adults with hearing loss and young, normal-hearing individuals. For dichotic stimuli, both subject groups showed a REA. As in agreement with other related studies, however, the older adults showed an exaggerated advantage for right-sided stimuli when compared to young adults. Grose attributes this large REA (also called LED) to decreased integrity of the highest levels of the auditory neural pathway, a process associated with aging.

Likewise, Noffsinger and colleagues (1996) also report a larger REA during dichotic listening for older adults compared to young adults when using three types of stimuli: digits, sentences, and nonsense syllables. The larger REA was displayed despite symmetrical hearing thresholds among the older adult participants. Roup et al. (2006) illustrated this same age-related performance pattern using dichotic word recognition performance. In a later study (2011), Roup demonstrated that adding speech-spectrum noise to dichotic words for young adults resulted in significantly poorer performance (more similar to older adults in the quiet dichotic paradigm) but significantly smaller REAs than the older adults. From this evidence, it is reasonable to conclude that, when compared to young adults, older adults exhibit a larger advantage when stimuli are presented to the right side as opposed to the left side in competitive listening situations. These studies thus provide evidence that an increasing REA seems to accompany increasing age, especially in the presence of sensorineural hearing loss.

Concerning the present study, the question arises: when does this difference in performance in dichotic listening begin to occur? Do middle-aged adults exhibit a performance pattern more similar to young adults or the more exaggerated REA found in older adults? Davis et al. (2013) used a “quasi-dichotic” paradigm to examine this question. In this scenario, the listener heard the target speech at the same level in both ears and heard the speech competitor at a greater intensity in the ear contralateral to the test ear. The researchers argued that this paradigm may involve the same processing involved in dichotic listening while at the same time be slightly more difficult than the typical dichotic listening method (since there are more signals competing with the target). Davis and colleagues examined performance on this task for middle-aged and young adult female participants via the N400 electrophysiological response in lieu of subject verbal recognition performance. Results indicated a slight but statistically-significant age-related decline in interaural symmetry for the most difficult task in the study. Specifically, the middle-aged adults showed increased responses when the probe stimulus was presented in the presence of a right-ear competitor than a left-ear competitor, consistent with an increased REA/LED. This interaural asymmetry was not exhibited in the young adult group. Although the researchers make an excellent argument for using this particular paradigm, the disparity in methodology between this study and previous dichotic listening studies make comparison across age groups somewhat difficult. Electrophysiological responses may involve different neural processes than behavioral responses, so a direct comparison between the two cannot be fully ascertained.

Stimulus Effects

Various stimuli can be used in dichotic listening tasks, and these are typically digits, consonant vowels (CVs, also called nonsense syllables), words, or sentences. Noffsinger et al. (1996) compared older adult performance using digits, sentences, and CVs. Noffsinger et al. showed better performance for digits and sentences, while CVs proved to be significantly more difficult to recognize (as expected). Additionally, the older adult subjects exhibited significantly lower performances for the left ear for CVs. The authors remarked that, as stimuli become more meaningless for an individual, they become more difficult for recognition and vice versa - as stimuli increase in their meaning, they also increase in their ability to be recognized. The duration of stimuli, as the researchers note, also affects recognition ability. CVs are short-duration stimuli and are all similar in duration time. In light of these characteristics (meaninglessness and short, similar duration), CVs present an added cognitive load and are very difficult for recognition in dichotic tasks, especially for older adults.

Roup et al. (2006) discussed how the type of stimulus affects the degree of difficulty of the dichotic listening task. A non-speech competing signal (i.e., broadband noise) provides little interference in recognition, while nonsense syllables provide the most difficulty. Monosyllabic words (i.e., the Northwestern University Auditory Test No. 6, or NU-6), however, exist as a favorable medium between these two stimuli and provide certain advantages for dichotic listening tasks by being neither too difficult (like the lack of familiarity associated with nonsense syllables) nor too easy (like the contextual information provided with sentences or the closed-set nature of digits). Additionally, monosyllabic words are in widespread use, are easily available in standardized formats, and have normative data available across different age groups. We can thus make better cross-study comparisons and more generalized conclusions with the use of these stimuli. Accordingly, Roup and colleagues make a strong argument for the use of monosyllabic words as dichotic stimuli.

Strategy Effects (Response Condition)

In addition to stimulus type, the way in which an experimenter instructs the listener affects performance. Response conditions can prompt the listener to use divided attention (known as free recall) or directed attention. In the free-recall condition, subjects are asked to recall the stimuli presented to both ears in any order. In contrast, the directed-recall condition cues the listener. The individual is instructed to recall stimuli in a specific order. For example, directed-recall right would require the participant to identify the stimulus in the right ear, followed by the stimulus in the left ear. This type of response condition therefore provides the participant with a strategy in processing the auditory information. The free-recall condition (often given first if used in dichotic testing) offers the listener no specific strategy and is therefore viewed as more challenging due to the increased cognitive load required. Given that cognitive decline is associated with the normal aging process, controlling for strategy effects in dichotic listening tasks is particularly important when comparing performance between age groups.

Handedness Effects

Handedness has also been shown to be a factor affecting dichotic listening performance. Specifically, right-handed individuals have been shown to be more lateralized than left-handed individuals for dichotic listening tasks. In reviewing multiple studies, Bryden (1988) reports an 82-percent occurrence of a REA in right-handers and only a 64-percent REA occurrence in left-handers. Using an equal number of right- and left-handers, Wilson and Leigh (1996) likewise found right-handed people to show a stronger, more consistent REA than their left-handed subjects. Left-handers exhibited more variability in performance, and this seemed to be somewhat dependent on the ear to which stimuli were presented - overall performance by right- and left-handers differed for right-ear stimuli but did not show this difference for left-ear stimuli. These results suggesting higher degrees of variability among left-handed listeners are consistent with other studies (Gelfand et al., 1980; Noffsinger, 1985). In light of this evidence, handedness is an important consideration for dichotic listening and should be recorded/measured and controlled for in any dichotic listening study.

Clinical Significance of the Present Study

Those who seek audiological services often report difficulty understanding speech, most notably in challenging, everyday listening situations (i.e., background noise). For those with bilateral hearing loss, binaural amplification can often provide not only improved audibility, but also help in restoring the typical advantages associated with listening with two ears. The binaural advantage, however, is not universal across all individuals, even in the presence of symmetrical hearing. As argued by multiple sources (i.e., Carter et al., 2001; Chmiel et al., 1997; Jerger et al., 1993; Walden & Walden, 2005), some individuals display greater benefit and/or prefer wearing one hearing aid as opposed to traditionally-prescribed binaural amplification. In these cases, which may be as high as 8 to 10 percent of older adults (Jerger et al.,1993), individuals display binaural deficits or binaural interference in lieu of a binaural advantage despite symmetrical hearing loss.

The dissatisfaction or unsuccessful use of amplification is of upmost importance in audiology, especially in today's age of rising healthcare costs and increased need for and awareness of effective verification measures. The typical clinical audiological test protocol (pure tone threshold testing, speech recognition in quiet) is not sensitive in detecting when an individual may be experiencing a binaural processing deficit. Those who may be displaying a lack of success with amplification may need further testing.

Including measures that “tax” the auditory system and provide information about more central auditory areas, such as speech recognition in noise and/or dichotic listening tasks, may present a more thorough and complete picture of a patient’s auditory system and the way in which we expect a patient to perform in “real world” listening situations.

The development and addition of useful clinical measures must begin with a body of research. Much of the research on age-related factors affecting binaural processing is focused on older adults (60+ years of age); a much smaller portion is dedicated to investigating middle-aged adults. There are gaps in our knowledge regarding binaural processing throughout the adult lifespan, which leaves us with many questions not only in terms of research purposes but also regarding effective clinical care throughout adulthood.

Although hearing loss prevalence increases with age and is therefore more common in older adulthood, a relatively significant portion of adults in middle age live with varying degrees of hearing loss (see Agrawal et al., 2008). Hearing loss in this age group is typically high-frequency sensorineural; thus, perceiving some of the low-intensity, high-frequency cues important for speech intelligibility can be challenging, especially in the presence of background noise. Yet, even middle-age adults with clinically-normal hearing sensitivity often report difficulty understanding speech in background noise, sometimes self-referring themselves for audiological testing due to these concerns (Helfer & Vargo, 2009; Leigh-Paffenroth & Elangovan, 2011). Understanding the root of these complaints may be key to better serving this population of individuals, as well as offering preventative strategies to assist in deterring further age-related declines as much as possible. For example, Ross et al. (2007) argue that if binaural processing abilities begin to decline in middle age, perhaps certain auditory training paradigms can be developed to promote compensation and prevent further difficulties in older age. In addition, as has been demonstrated with older adults, gaining a better understanding of performance patterns in this population may support the development of certain clinical assessment and treatment strategies (i.e., monaural instead of binaural use of amplification in noise) that may lead to greater benefit and success in those with binaural processing deficits.

Present Study

The present study aimed to assess binaural processing abilities of middle-aged adults and compare these results with previously-collected data from normal hearing young adults and older adults with sensorineural hearing loss. To assess binaural processing ability, two types of behavioral tasks were used: (1) monaural right, monaural left, and binaural diotic word recognition in multitalker babble at various signal-to-babble ratios and (2) free recall, directed-recall right, and directed-recall left dichotic listening tasks.

Past related studies have shown that adults with hearing loss and binaural processing deficits may have more success using one hearing aid rather than two, and/or using an FM system rather than hearing aids alone (Carter et al., 2001; Chmiel et al., 1997; Holmes, Walden & Walden, 2005). If binaural processing deficits are indeed associated with biological changes due to aging, at what point in the human lifespan does this begin to affect performance, and is it earlier than previously investigated (the sixth decade of life)? The majority of previous related studies focus on the older adult population and very little of this binaural hearing research is dedicated to the middle-aged adult population. The research that has focused on this population, although relatively sparse, suggests that decrements in binaural processing may occur earlier in adulthood than previously suspected and that this may affect an individual's ability to process signals in more challenging, everyday environments. How can we improve our understanding, approach, and services to better meet the needs of these individuals, many of whom may not be appropriate candidates for typical audiological rehabilitation strategies (i.e. amplification)?

CHAPTER 3

METHODS

Participants

The present study assessed 30 middle-aged adults, ages 31-59 years, categorized into three subgroups: 10 participants ages 31-39 years, 10 participants ages 40-49 years, and 10 participants 50-59 years. Based on prevalence data showing that normal hearing ranging to mild high-frequency sensorineural hearing loss is common within this population (Agrawal et al., 2008), all subjects were required to have pure-tone thresholds within normal limits through 500 Hz and thresholds no worse than 40 dB HL through 4000 Hz.

Previous studies have demonstrated that the REA is likely to vary with handedness; right-handed individuals typically possess stronger REAs and seem to have less inter-subject variability than those who are left-handed or ambidextrous (Wilson & Leigh, 1996). In attempt to account for this variability, only right-handed individuals were recruited. Right-handedness was confirmed for all subjects via the Edinburgh Handedness Inventory, a measure in which subjects rate their hand preference(s) for ten common tasks in everyday life (Oldfield, 1971). Inclusion criteria for this inventory was a laterality quotient > 40.

All participants were asked to provide a brief audiologic case history and were given a complete pure-tone audiometric assessment (octave frequencies from250-8000 Hz) to confirm normal hearing or no more than a mild high-frequency sensorineural hearing loss and no conductive components. Symmetrical air conduction thresholds (no greater than a 10 dB HL difference between ears) through 4000 Hz were required, along with no significant air-bone gaps. Additionally, all subjects possessed normal otoscopic findings (no drainage, impacted cerumen, etc.); no significant history of ear pathology; normal tympanometric measures; no history of ototoxic medications; and generally good overall health. Participants were recruited from The Ohio State University and the greater Columbus, Ohio community. Figure 1 illustrates pure-tone audiometric data (averaged across ear and across participant) for the middle-aged adult group.

Stimuli

Two types of speech-recognition assessments were used: (1) monaural and diotic binaural word recognition in noise and (2) dichotic word recognition. For both types of assessments, the Northwestern University Auditory Test No.6 (NU-6) monosyllabic words spoken by a female speaker from the Department of Veterans Affairs compact disc *Speech Recognition and Identification Materials 1.1* (VA Medical Center, Long Beach, CA, 1991) were used. NU-6 words are monosyllabic phonetically-balanced words commonly used in clinical audiology to measure speech understanding.

A two-channel CD recording of 100 NU-6 dichotic word pairs were used to measure dichotic word recognition (Roup et al., 2006). Specifically, individual NU-6

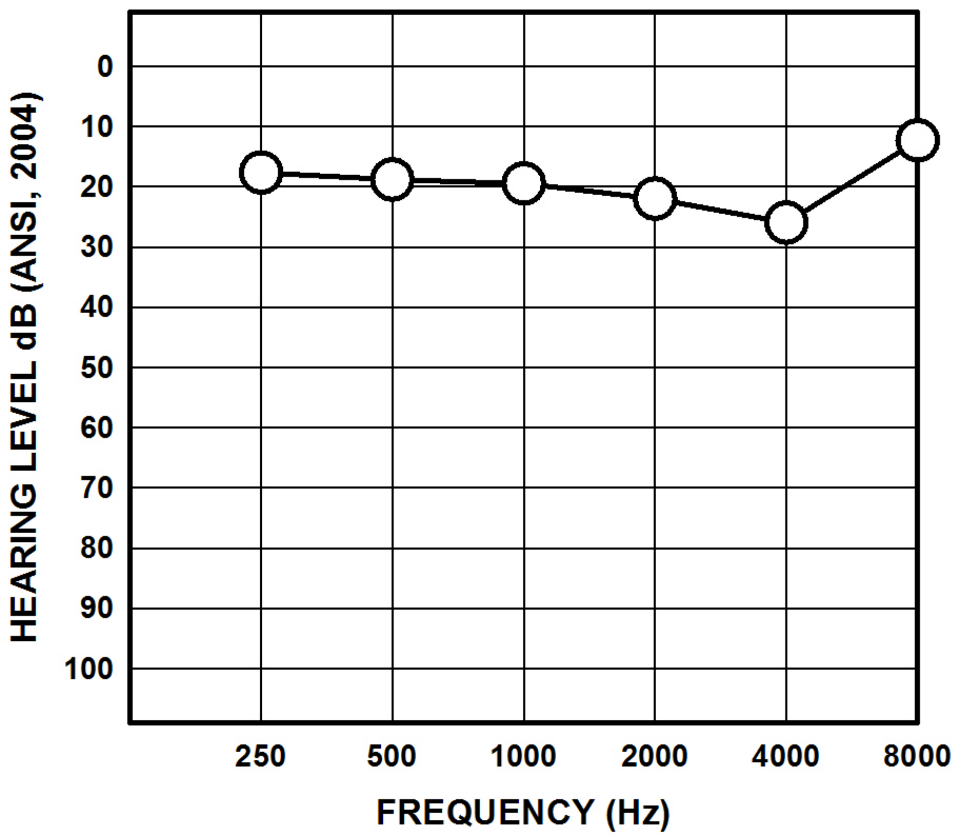


Figure 1. Average (across ear and across participants) pure-tone thresholds (in dB HL) for middle-aged adults across all frequencies tested.

words were paired so that the presentation of the carrier phrase, “Say the word” and the NU-6 words occurred essentially simultaneously on the two channels. Word pairings with similar initial and final consonants were avoided. Similarly, a two-channel CD recording of the 200 NU-6 words and multitalker babble was used to measure monaural and binaural word recognition performance. Specifically, six randomizations of the NU-6 word lists were generated and recorded on channel 1 with the multitalker babble recorded on channel 2 of the CD. The multitalker babble is a 6-talker babble consisting of three men and three women (Sperry et al., 1997). The interstimulus interval for both the dichotic words and words in multitalker babble was 4.5 seconds.

Procedures

Subjects participated in one to two sessions lasting approximately one to one and a half hours consisting of two experimental conditions: dichotic word recognition and word recognition in multitalker babble. For the dichotic listening tasks, the subjects responded in three response conditions: (1) free recall (repeat both stimuli in any order); (2) directed recall-right (repeat the stimulus from the right ear, followed by the stimulus from the left ear); and (3) directed-recall left (repeat the stimulus from the left ear, followed by the stimulus from the right ear). For each subject, free-recall was presented first in order to prevent subject’s employing a specific listening strategy. The directed recall conditions (right and left) were presented after the free-recall condition and were counterbalanced across subjects. A minimum of five practice trials were given in order to familiarize the subject with each response condition. No feedback on performance was provided, but verbal encouragement was given.

For word recognition in multitalker babble, the subjects responded in three response conditions: (1) monaural left; (2) monaural right; and (3) diotic binaural. In order to create a psychometric function [performance in percent by signal-to-babble ratio (SBR)], words were presented at five SBRs. These SBRs ranged from 0 dB SBR to +16 dB SBR in 4 dB steps. To alter the SBR, the presentation level of the target words was held constant while the level of the multitalker babble was varied. A list of 25 words was presented twice at each SBR, once on a descending run and once on an ascending run, for a total of 50 words per SBR. The presentation order of each response condition and ascending/descending run were counterbalanced across subjects.

The experimental speech stimuli were routed from a CD player (Sony CE375) to a 2-channel audiometer (Grason Stadler 61) and presented via Etymotic ER-3A insert earphones. The presentation of the speech stimuli was held constant at a level that was to be determined by the participant's pure-tone thresholds. If the participant displayed a three-frequency pure-tone average (PTA) of 20 dB HL or less, the speech stimuli for each condition were presented at 50 dB HL. Because all subjects in this study exhibited PTAs no greater than 20 dB HL, the presentation level for all individuals was 50 dB HL.

All experimental testing was conducted in a sound-attenuating booth. The testing equipment (audiometer and tympanometer) was calibrated according to the appropriate American National Standards Institute (ANSI) standards (ANSI, 2004, 1987) at the beginning of the study and at subsequent 6-month intervals. Biologic checks were conducted daily to confirm that the equipment continued to properly function.

CHAPTER 4:

RESULTS

Descriptive Statistics

Middle-aged adult group means and standard deviations for NU-6 word recognition in multitalker babble are displayed in Table 1 for all SBRs in all response conditions (monaural right, left, and binaural). Group performance of young and older adults for the same task are also presented in Figure 2. Note that due to varying ages and hearing sensitivity, different SBRs were used for each age group. Each group was tested at 5 different SBRs, and the three age groups shared three common SBRs (+4, +8, and +12 dB SBR).

Young adults performed better than middle-aged and older adults at all common SBRs in all conditions, and middle-aged adults performed better than older adults at all common SBRs. These general performance patterns follow the initial hypothesis of group trends. For all three age groups, mean recognition performance was similar for the left and right monaural conditions, and the binaural condition resulted in the best performance for each SBR. There was one exception: middle-aged adults showed the exact same mean performance for the right, left, and binaural condition at +16 SBR.

Displayed in Figure 2 are performance functions for all three age groups for the binaural and average monaural (calculated by averaging right and left monaural

Table 1. Mean word recognition performance (in percent correct) and standard deviations for young, middle-aged, and older adult groups at all SBRs across all response conditions (monaural right, left, and binaural).

		Signal-to-Babble Ratios						
		-4 dB	0 dB	4 dB	8 dB	12 dB	16 dB	20 dB
Young Adults								
Right Ear	Mean	15.07	39.40	62.07	76.73	85.93		
	SD	5.14	6.48	8.51	7.82	4.68		
Left Ear	Mean	16.20	38.33	59.20	73.80	83.27		
	SD	5.93	9.34	7.69	8.73	7.83		
Binaural	Mean	24.33	44.27	63.47	80.20	88.60		
	SD	8.82	9.93	9.51	4.62	4.85		
Middle-Aged Adults								
Right Ear	Mean		35.27	60.87	73.00	85.53	89.87	
	SD		9.34	10.59	11.35	5.50	5.30	
Left Ear	Mean		35.67	58.00	73.13	84.07	89.87	
	SD		9.44	9.37	9.75	8.53	4.20	
Binaural	Mean		44.00	63.33	78.27	87.47	89.87	
	SD		11.31	7.85	6.45	5.92	5.25	
Older Adults								
Right Ear	Mean			17.03	33.47	50.07	62.07	69.27
	SD			12.30	16.56	19.00	21.80	19.30
Left Ear	Mean			15.27	32.07	47.87	62.53	69.07
	SD			11.92	16.02	17.26	19.92	16.57
Binaural	Mean			23.60	40.60	59.20	70.60	76.80
	SD			13.37	17.83	18.73	16.40	15.90

performance) conditions. The bold black line in the center of the figure represents 50%-correct performance; therefore, the points at which each function is intersected by this line (in dB SBR) represent 50%-correct thresholds. The 50% threshold represents the average dB SBR needed to achieve 50%-correct recognition for that particular condition. These 50%-correct thresholds for the psychometric functions were calculated using the Spearman-Kärber method (Finney, 1952). For all groups, the binaural 50%-correct threshold (1.97, 3.48, and 11.17 dB SBR for young, middle-aged, and older adults, respectively) was lower than the average monaural conditions (3.00, 4.30, and 11.50 dB SBR), indicating better recognition performance in the binaural condition. Considering the binaural advantage, this finding also follows hypothesized trends in group performance.

In addition to thresholds, slopes of the performance functions were also calculated. Using linear regression, the slope of each function was calculated using all data points for binaural and average monaural performance. As expected, young adults displayed the steepest (greatest) slopes for both the binaural and average monaural functions, indicating greater improvements in performance for each increase in SBR. Middle-aged adults showed shallower slopes than young adults but steeper slopes than older adults for both the binaural and average monaural functions.

The benefit in performance gained from binaural versus monaural listening, or binaural benefit, in MTB for each group is displayed in Figure 3. Binaural benefit was calculated by subtracting the average monaural performance score (in percent correct)

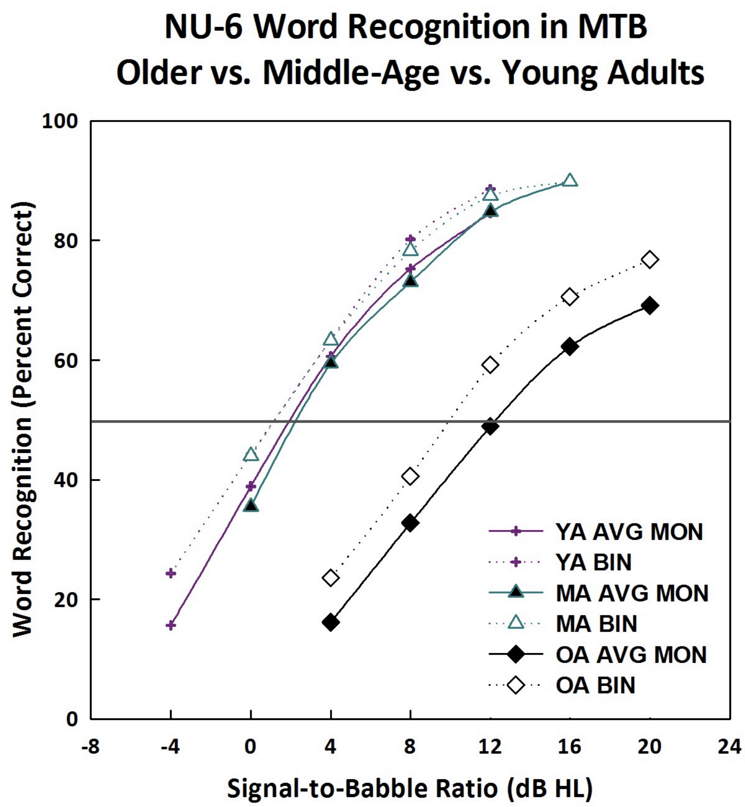


Figure 2. Performance functions for mean NU-6 recognition (in percent correct) across SBR for young adults (YA), middle-aged adults (MA), and older adults (OA) for the binaural and average monaural (average of monaural right and left performance). The bold black line represents the 50%-correct threshold line.

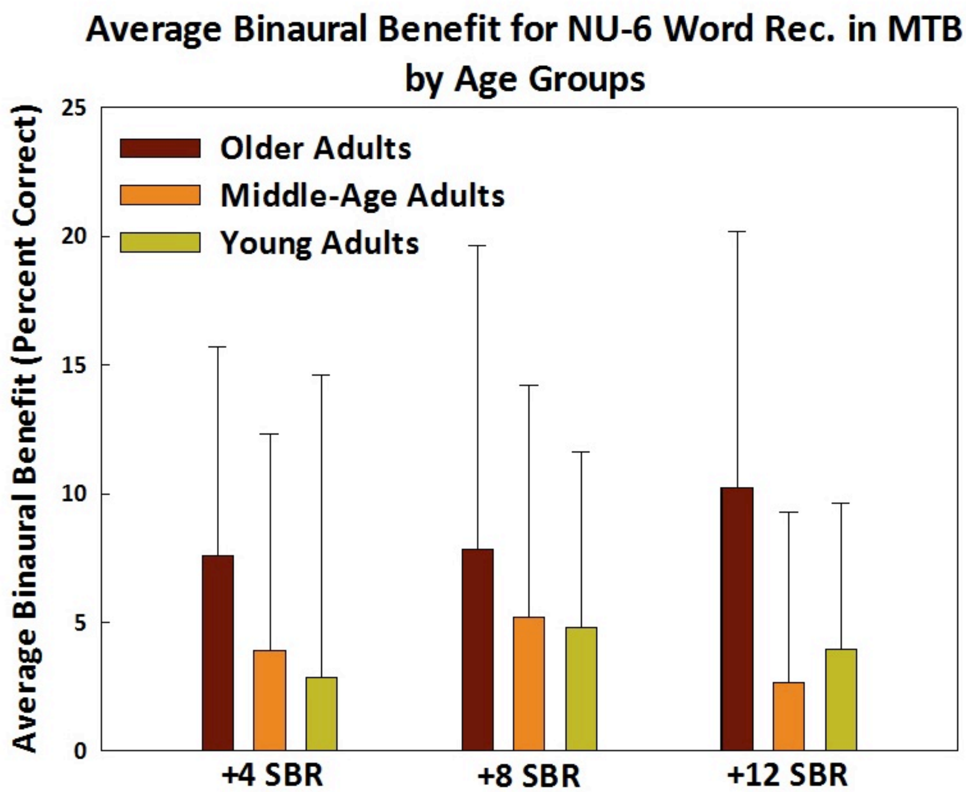


Figure 3. Average binaural benefit (binaural performance – average monaural performance) for word recognition in MTB for *common* SBR across age groups. Error bars indicate one standard deviation.

Table 2. Mean dichotic word recognition performance (in percent correct) and standard deviations for young, middle-aged, and older adults across all response conditions: free recall, directed right and directed left.

		Right Ear	Left Ear	RE-LE (Ear Advantage)
Young Adults				
Free Recall	Mean	83.27	81.47	2.53
	SD	7.42	8.39	8.71
Directed Right	Mean	88.87	80.00	8.87
	SD	5.79	8.68	9.11
Directed Left	Mean	84.33	87.20	-2.73
	SD	8.47	5.96	7.40
Middle-Aged Adults				
Free Recall	Mean	79.47	77.27	2.20
	SD	9.42	11.84	9.01
Directed Right	Mean	87.20	74.13	13.07
	SD	6.42	13.50	11.13
Directed Left	Mean	78.40	86.53	-8.13
	SD	11.64	7.20	8.79
Older Adults				
Free Recall	Mean	50.20	45.60	4.67
	SD	26.55	24.52	23.00
Directed Right	Mean	58.00	41.27	16.73
	SD	26.11	25.92	19.07
Directed Left	Mean	46.27	55.47	-9.20
	SD	24.20	24.74	16.75

from the binaural performance score at each SBR. Because various SBRs were used for each age group, only three SBRs (+4, +8, and +12 SBR) were common among all three groups and consequently only three sets of binaural benefit graphs are displayed in the figure. It is evident that, at all common SBRs, older adults exhibited a greater binaural benefit when listening to words in MTB compared to young and middle-aged adults.

Table 2 presents group mean performance for the dichotic word recognition task for each ear across all response conditions. As expected, the young adult group performed better overall on average in dichotic word recognition performance compared to the middle-aged and older adult groups across all response conditions. Ear advantage (EA) is a useful measure when examining ear preference in dichotic listening. To calculate EA, percent correct recognition for the left ear was subtracted from percent correct from the right ear for each condition. A positive EA would therefore indicate a REA, and a negative EA would indicate a LEA. In addition to right- and left-ear performance for each condition, Table 2 also lists EAs for all subject groups.

Additionally, Figure 4 displays dichotic performance as boxplots in the free recall condition for each group. The boundaries of the body of the boxplot represent the 25th (lower boundary) and 75th (upper boundary) percentiles, and the means and medians of each data set are represented by the black and yellow lines, respectively, within the boxplot body. Outliers are indicated by the black dots at or beyond the whiskers of the boxplots. Variability in performance for each group can easily be visualized by the length of each boxplot. As shown, young adults showed the lowest degree of inter-individual

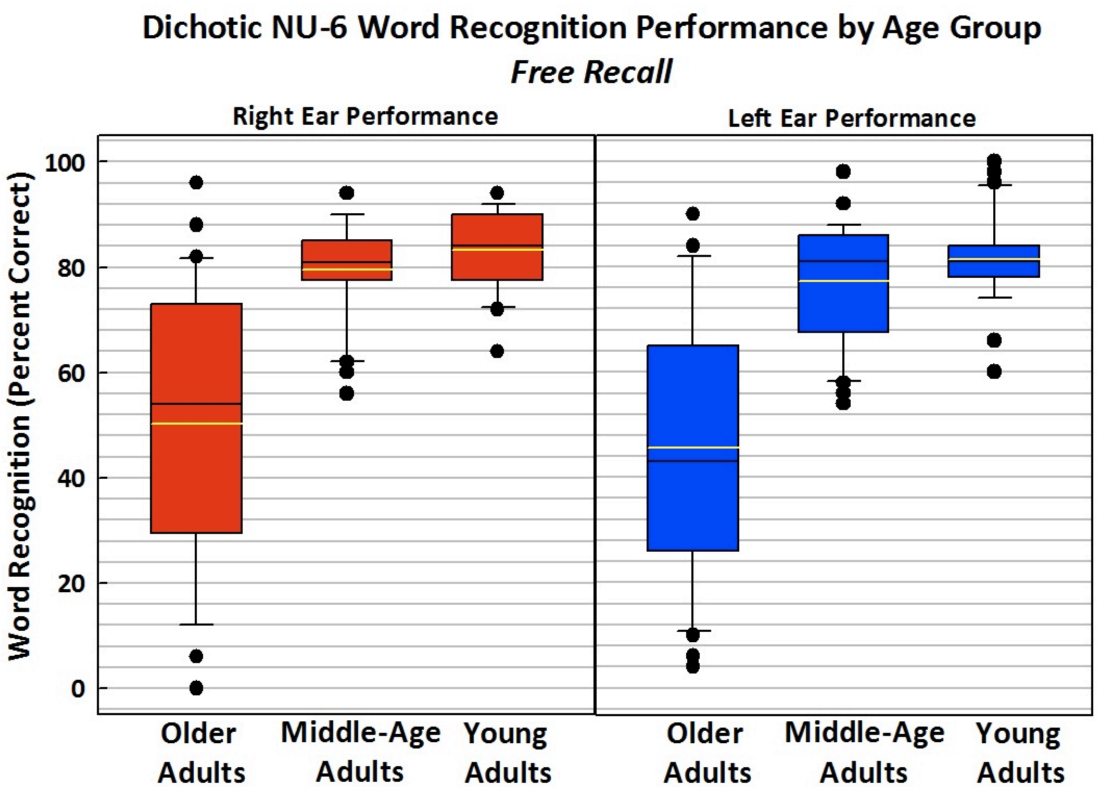


Figure 4. Mean dichotic performance (in percent correct) by ear for young, middle-age, and older adults in the free recall condition. Medians for each box plot are indicated by the yellow line; means are indicated by the black line. The black dots at or beyond the whiskers of each boxplot represent outliers.

variability in performance. Middle-aged adults showed a greater degree of variability from one individual to the next, and older adults displayed the greatest amount of variability.

All three age groups exhibited the expected pattern of performance for dichotic listening at the group level: a mean REA in the free recall condition, a larger REA in the directed right condition, and a LEA in the directed left condition. As expected, the directed response conditions resulted in overall better performance for all groups and increased ear advantages for the side to which the subject was directed: directed right resulted in larger REAs (8.87% EA for young adults, 13.07% EA for middle-aged adults, and 16.73% EA for older adults), and directed left resulted in LEAs for all groups (-2.73% EA for young adults, -8.13% EA for middle-aged adults, and -9.20% EA for older adults).

Statistical Analysis

Due to the error in variance associated with percentage data, rationalized arcsine units were calculated from percentage data to use for statistical analysis (Studebaker, 1985). The 50%-correct thresholds were compared using a repeated-measures analysis of variance (ANOVA) to determine if there were significant differences in word recognition performance across response conditions. For all groups, the right- and left-ear performances were not found to be significantly different in word recognition ($p > .05$). Word recognition performance data for the monaural left and monaural right conditions were thus collapsed, and the combined monaural data were compared to binaural performance for 50%-correct thresholds.

Significant differences in recognition performance between the monaural and binaural conditions were revealed for the young, middle-aged, and older adult groups. Specifically, binaural recognition performance was found to be significantly better than monaural recognition performance for all subject groups at 50%-correct thresholds [$F_{(1,87)}$=6.51; p<.05]. A significant main effect of group [$F_{(2,87)}$=211.45; p <.05] was revealed for thresholds as well. A post-hoc Bonferroni paired t-test revealed significant differences in the 50%-correct thresholds existed between groups for both the average monaural and binaural conditions. The young adults exhibited significantly lower (or better) thresholds than both middle-aged and older adults, and the middle-aged adults showed significantly lower thresholds than older adults.

Similarly, a repeated-measures ANOVA was used to assess whether there were significant differences in the slope of the performance functions for NU-6 word recognition in noise. Just as with thresholds, the slopes for the monaural and binaural conditions were found to be significantly different from each other [$F_{(1,87)}$=9.44; p<0.05]. There was also a significant main effect of group [$F_{(2,87)}$=26.47; p<0.05]; a post-hoc Bonferroni paired t-test revealed that this statistical significance only existed between the young adults and the middle-aged and older adults. The middle-aged and older adults did not significantly differ from each other in the slopes of their functions.

A two-way repeated-measures ANOVA was also conducted to determine if significant differences existed for the dichotic word recognition task. Condition and ear were within-subjects factors. For all age groups, no significant differences in dichotic word recognition performance between right and left ears in the free recall condition were found. There was, however, a significant main effect of group in free recall, directed right, and direct left [$F_{(2,87)}=44.44$; $p<0.05$]. Post-hoc Bonferroni paired t-tests showed a significant difference in performance between middle-aged and older adults for both the right and left ears in all dichotic conditions, with middle-aged adults performing significantly better than older adults. Young adults performed significantly better than older adults but not middle-aged adults for free recall, directed right, and directed left.

Individual Results

Although group performance trends seem to reflect initial expectations, examining individual data shows some interesting variation in performance. Reflected in the standard deviations and also graphically in the boxplots in Figure 4, middle-aged and older adults demonstrated considerable variation in their responses for both tasks. This inter-individual variability is highlighted with several individuals shown in Figures 5, 6, and 7. Figure 5 displays the performance data of a 38-year-old female. This individual exhibited what is considered an expected or “typical” pattern of performance. She showed better performance in the binaural condition than in either monaural condition for word recognition in MTB, and both monaural condition recognition performances

Figure 5

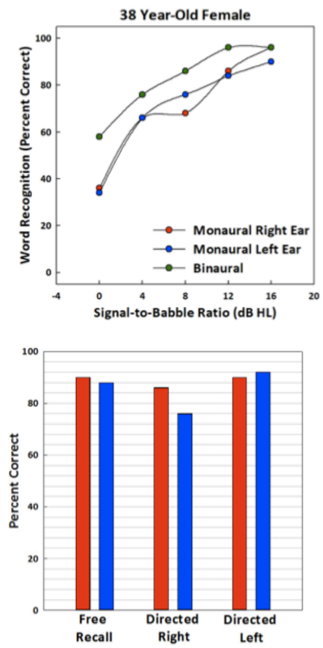


Figure 6

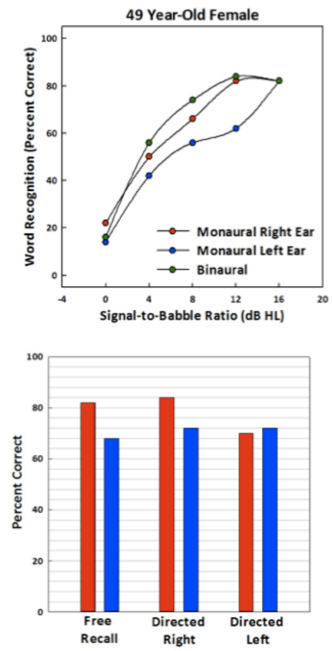
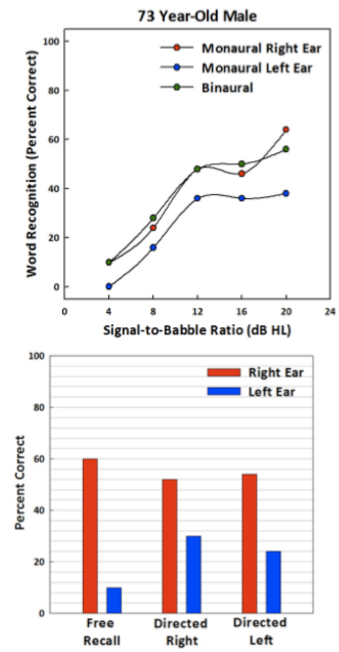


Figure 7



Figures 5, 6, & 7. Individual data are presented for (top panels) NU-6 in MTB word recognition performance (in percent correct) for monaural right, left, and binaural conditions and (bottom panels) dichotic word recognition performance for the right and left ears in free recall, directed right, and directed left conditions for a 38-year old female (**Figure 5**, left), a 49-year old female (**Figure 6**, middle), and a 73-year old male (**Figure 7**, right). Red bars indicate right-ear performance; blue bars indicate left-ear performance. Figure 5 exhibits "typical" results for each task, specifically: (1) a slight REA for free recall, larger REA for directed right, and a LEA for directed left; and (2) better recognition performance in the binaural condition compared to right and left monaural conditions for all SBRs and similar right and left monaural recognition performance. Figures 6 and 7 display more unexpected trends in performance.

were similar. For the dichotic listening task, this subject exhibited a slight REA for the free recall condition, an increased REA for the directed right condition, and a LEA for the directed left condition. This individual's performance pattern coincides with the overall group pattern.

In contrast, Figures 6 and 7 show data for a 49-year-old female and a 76-year-old male, two participants who exhibited "atypical" results, or unexpected patterns of performance for the experimental tasks. Compared to group data, the 49-year-old female displayed overall poorer performance for both tasks. Further, she displayed a trend of poorer-than-expected left-ear compared to right-ear performance for both tasks despite symmetrical hearing acuity. As shown in Figure 6, the monaural right condition resulted in consistently better performance than monaural left in the word recognition task, and there is a more exaggerated REA in the free recall dichotic condition than expected, almost equal in magnitude to the directed right condition.

In Figure 7, the performance of a 76-year-old male participant demonstrates an even clearer atypical pattern of performance for each task. Specifically, this individual consistently performed better in the monaural right than the monaural left condition for the word recognition in MTB task. He lacked a clear binaural advantage and actually showed equal to or better recognition performance for the monaural right condition than the binaural condition for some SBRs. For the dichotic listening task, this individual showed an exaggerated REA for *all* response conditions. Even when directed to his left ear during dichotic listening, this individual possessed a strong REA. Furthermore, he consistently displayed better right-ear recognition performance compared to left ear for all SBRs and no consistent binaural advantage for word recognition in MTB. When considering the “typical” pattern of results displayed by the mean data of the 3 age groups, the performance patterns of the aforementioned two individuals displayed in Figures 6 and 7 clearly differ (in varying degrees) from the group mean data.

CHAPTER 5:

DISCUSSION

The present study assessed monaural and binaural processing of middle-aged adults by using two tasks of speech recognition in competitive listening situations. Two main questions were explored: (1) What is the relationship between dichotic listening and left-ear, right-ear, and diotic binaural word recognition in noise among middle age adults (ages 31-59 years)?; and (2) How does recognition performance compare to previously-collected data of the same tasks for normal hearing young adults (18-30 years) and older adults with hearing loss (60-89 years)?

Through an examination of the patterns of performance at both the group and individual levels, the relationship between dichotic word recognition and word recognition in noise can be understood. As mentioned, a subject/group performs "typically" when displaying relatively similar monaural word recognition in noise scores and improved binaural word recognition in noise performance relative to monaural performance (in other words – a binaural advantage). For dichotic word recognition, a typical right-handed listener will show a slight REA in the free recall condition, an increased REA in directed right, and a LEA in the directed left condition. A participant's (or group's) performance patterns for both sets of tasks are then cross-compared to determine if binaural or monaural processing in competitive listening situations results in the best performance for a particular participant/group and how this compares to other expected performance patterns.

Overall group performance for middle-aged adults on the word recognition in noise task coincided with the expected patterns of performance. The group showed no significant difference in right- and left-ear monaural performance and significantly better performance in the binaural condition relative to average monaural performance at all SBRs. This result confirms that the middle-aged adult group exhibited a binaural advantage in noise. Middle-aged adult 50%-correct thresholds for word recognition performance functions were comparable for the right and left ears (RE: 3.35 dB SBR, LE: 3.36 dB SBR), with no significant difference in word recognition between the two monaural listening conditions. The significantly-lower 50%-correct threshold for the binaural condition (2.90 dB SBR) demonstrates the advantage gained when using both ears in a competitive listening environment.

Likewise, the middle-aged adults performed as expected on the group level for the dichotic word recognition task. They showed a group mean REA in the free recall condition, a larger REA in the directed right condition, and a LEA in the directed left condition. Because all subjects were right-handed, better recognition of stimuli presented to the right ear during free recall was anticipated based on language lateralization and the organization of the auditory system, as discussed by Kimura (1961). The directed response conditions resulted in overall better performance for this group, indicating that offering the subjects a strategy results in better performance.

Additionally, the middle-aged listeners demonstrated increased ear advantages for the side to which they were directed: directed right resulted in larger REAs, and directed left resulted in LEAs, coinciding with the expectation that directing a subject to a particular ear will result in better recognition of stimuli presented to that ear due to increased attention to that particular stimuli. In sum, an examination of the word recognition in noise and dichotic group data would indicate they showed performance patterns that, when examined overall and in isolation, met expectations.

Data from the present study were then compared to previously-collected data for young adults (ages 18-30 years) with normal hearing and older adults (ages 60-89 years) with sensorineural hearing loss for the same listening tasks. As the results of the study convey, middle-aged adults as a group seem to perform more similar to young adults than older adults. A cursory examination of the figures for the word recognition in noise and dichotic listening tasks verifies the seemingly similar performances of these groups. Yet, a closer examination of the data shows that there are subtle differences between these two groups that warrant discussion. Although there is a more definite separation in performance between middle-aged and older adults than between young and middle-aged adults, there is arguably a trend of slightly-decreased performance for middle-aged adults compared to young adults for the tasks in this study.

With the exception of +12 SBR in the monaural left condition, the young adult group outperformed the middle-aged adults at all common SBRs for the word recognition in noise task. As expected, the young and middle-aged adults performed better than the older adults at all common SBRs in all conditions. When examining 50%-correct thresholds, however, the young adults exhibited a significantly lower SBR threshold for both the binaural and average monaural conditions (1.97 and 3.00 dB SBR, respectively) than both middle-aged (3.48 and 4.30 dB SBR) and older adults (11.17 and 11.50 dB SBR), and the middle-aged adults exhibited significantly lower SBR binaural and average monaural thresholds than the older adult group. Based on this result, one could deduce that, although middle-aged adults appear to perform more similarly to young adults than older adults, they nevertheless experience more difficulty and require a more favorable signal-to-noise ratio for comparable word recognition performance in noise.

Correspondingly, young and middle-aged adults differed significantly in the slope of their group performance functions. In fact, the middle-aged adults were found to significantly differ from young adults, but not older adults on their average monaural performance function slopes. By demonstrating a steeper slope in performance for both binaural and average monaural conditions, young adults showed greater improvements for each increase in SBR. These results suggest that, although the young and middle-aged adult groups had similar hearing thresholds, the middle-aged adults did not have the same efficiency at using improvements in the SBR to produce corresponding improvements in recognition performance.

Another meaningful point of comparison between the groups is the magnitude of binaural benefit achieved in the word recognition in noise task, as outlined in Figure 3.

Average binaural benefit is calculated by subtracting average monaural from binaural performance, and this figure displays binaural benefit for each group for common SBRs (+4, +8, and +12 dB SBR). Binaural benefit is also visually demonstrated by the degree of separation between the binaural and monaural performance functions for each group displayed in Figure 2. Older adults noticeably show greater degrees of binaural benefit, or a larger binaural advantage in noise, than their middle-aged and young adult counterparts. These results suggest that aging, particularly after age 60 years, may be accompanied by an increased binaural benefit for speech understanding in noise. Compared to young and middle-aged adults, binaural listening may therefore be more important for older adults with sensorineural hearing loss when listening to speech in noisy environments.

For the dichotic listening task, the middle-aged adult group exhibited the expected pattern of performance: a slight mean REA for the free recall condition (2.20% EA) and larger mean ear advantages for the directed attention conditions (13.07% EA for directed right; -8.07% EA for directed left). The young adult group showed this same pattern of performance: a slight REA in free recall (2.53% EA) with reduced ear advantages in the directed conditions (8.87% EA for directed right; -2.73% EA for directed left) relative to the middle-aged adults. Of all three age groups, the older adult group exhibited the greatest magnitude of ear advantages in the free recall (4.67% EA) and directed conditions (16.73% EA for directed right; -9.20% for directed left).

These overall patterns in dichotic word recognition performance are in conjunction with previous research on dichotic listening (i.e., Noffsinger et al., 1996; Roup et al., 2006). Among right-handed individuals, a slight REA is expected when no listening strategy is presented to the participant. Kimura (1961) outlines the reasoning for this phenomenon via a discussion of language lateralization and the structure of a typical auditory system. The contralateral pathways of the auditory system are stronger and more developed than the ipsilateral pathways, making them more efficient for transference of signals. Considering this, a signal presented to the right ear will more efficiently be relayed to the contralateral (left) hemisphere. Most individuals, especially those who are right-handed, lateralize language in the left hemisphere of the cortex, so a signal presented to the right ear will be more readily available for recognition due to the more direct pathway it travels. Those signals that are presented to the left ear, however, must first travel to the right hemisphere then crossover via the corpus callosum (the nerve tracts connecting the two hemispheres) to the left hemisphere before it is recognized. When in a challenging listening environment with competing signals, a typical right-handed individual will consequently tend to show a stronger preference for materials presented to the right ear than stimuli presented to the left ear.

Group results from the present study are consistent with findings from previous research on behavioral dichotic listening tasks. Jerger and Jordan (1992), Carter and colleagues (2001), and Roup et al., (2006), for example, all report slight mean REAs among young adults and increased mean REAs for older adults (relative to young adults) in the free recall condition. The present study mirrored these same patterns of performance among young and older adults. The change in ear advantages observed with directed-attention dichotic listening tasks (i.e., a larger REA in directed right and a LEA in directed left) is similarly confirmed by Carter and colleagues (2001). When a listener's attention is directed to a certain side and he/she is therefore given a strategy, the cognitive demands of the task are reduced. Consequently, an increase in performance for the ear to which the subject is directed is typically observed, as exhibited by Carter et al. Indeed, all groups in the present study exhibited larger REAs in directed right and LEAs in directed left. Compared to young adults, older adults showed exaggerated ear advantages for the directed conditions as well as free recall, and the present study showed that middle-aged adults display ear advantages in the directed conditions at a magnitude between young and older adults. Again, these results could be argued to suggest that, though they may not experience binaural processing behavioral changes to the same degree that older adults exhibit, middle-aged adults nevertheless experience notable changes in performance in competitive listening environments when compared to young adults.

There is limited research available that specifically examines behavioral dichotic listening profiles of middle-aged adults compared to young and older adult age groups. A recent study by Davis et al. (2013), however, does provide some evidence to suggest that middle-aged women listeners may possess stronger right-ear preference in competitive listening situations compared to their young adult counterparts. Using electrophysiological measures and quasi-dichotic listening paradigm, Davis et al. (2013) examined interaural asymmetry in dichotic listening for middle-aged adults. Comparing data from young and middle-aged (ages 44-57 years) adult female participants with normal hearing, the study showed that middle-aged women showed a greater N400 response for speech directed to the right compared to the left ear. Davis and colleagues concluded that these results indicate that middle-aged women, even those with normal hearing, may possess a left-ear deficit in competitive listening situations when compared to young adult women. This interaural asymmetry difference is not as large as the interaural asymmetry difference between young adults and older adults (ages 60-90 years). Yet, it does offer insight to some age-related changes to the binaural auditory system that may occur in middle age, and the current behavioral study showing more dramatic ear advantages among middle-aged adults may lend support to this electrophysiological evidence.

Although group mean performance for the tasks in this experiment showed middle age adults performed more similar to young than older adults, middle-aged adults demonstrated considerable inter-individual variability in performance. Examining middle-aged and older adult data at the individual level displays this variability quite considerably. As demonstrated by the standard deviations in Tables 1 and 2 and the boxplots in Figure 4, older and middle-aged adults were more variable in their performances than young adults for both tasks of speech recognition. Figures 5-7 highlight the performance of three individuals, two middle-aged adults and one older adult. Figure 5 shows the results for a 38-year old exhibiting a “typical” or expected performance, namely: (1) similar right- and left-monaural recognition performance and better recognition performance in the binaural condition compared to both right and left monaural conditions for all SBRs; and (2) a slight REA for the free recall dichotic condition, a larger REA for directed right, and a LEA for directed left.

In contrast, Figures 6 and 7 display more unexpected trends in performance. Results for a 49-year-old individual are shown in Figure 6. For word recognition in noise, she consistently exhibited markedly poorer monaural left compared to monaural right performance and did not display a clear binaural advantage across all SBRs. Further, she presented with a large REA in the free recall condition and overall performed poorly on both tasks compared to other middle-aged adults. Although this performance pattern does not fit the classical pattern of a true binaural processing deficit (i.e., binaural interference), this individual nevertheless exhibits poorer-than-expected performance in competitive listening environments despite having no more than a mild high-frequency hearing loss that is symmetrical in nature.

The performance pattern displayed in Figure 7 is that of a clear binaural processing deficit. This 73-year-old male, despite having symmetric hearing sensitivity, demonstrates a distinct left-ear disadvantage when asked to recognize speech in the presence of competing signals. For word recognition in noise, this individual performed considerably worse in the monaural left condition compared to monaural right and did not exhibit any binaural advantage. Additionally, he showed a substantial REA in *all* dichotic conditions, even in directed left. As pointed out previously, this performance, which implies a binaural processing deficit, was exhibited by a subject who possesses symmetrical hearing thresholds.

For those individuals who may be displaying abnormal or poorer-than-expected binaural processing based on these listening tasks, the clinician is then pointed in the direction to consider alternative approaches to counseling and treatment. Although the individual's audiogram and word recognition in quiet score may suggest treating both ears equally – which in most cases means a binaural hearing aid fitting – performance on more taxing auditory tasks (as in this experiment) warrants deeper consideration. Clinically, this information could help better guide the audiologist in several ways. Perhaps it simply means regularly monitoring the individual's binaural processing performance using difficult listening tasks like dichotic listening and word recognition in noise. For those who may benefit from amplification, it might mean pursuing a monaural fitting instead of the more traditional binaural fitting and/or recommending the use of an assistive listening device that increases the signal-to-noise ratio (i.e., an FM system). The individual may also significantly benefit from a discussion about how to implement better communication strategies. Using the listening tasks that were implemented in this experiment, then, can arguably provide valuable information not typically gathered with the typical audiological battery. Effectively identifying an individual who may have abnormal patterns of binaural processing could potentially lead to a more self-aware, empowered, and satisfied patient.

The individual outcomes outlined from the present study emphasize the importance of examining results at both the group and individual level. Though the group performances are interesting in that they summarize trends in how we might expect aging to affect binaural processing in difficult listening environments for the average person, analyzing individual results can tell us a very different story. Given the higher degree of inter-participant variability among middle-aged and older adults, we realize the importance of considering each person as a part of a particular group yet at the same time a unique participant who may not perform in the "typical" way we expect. In this particular experiment, we cannot assume that every middle-aged individual will follow the group trend of relatively equal monaural performance and a binaural advantage in competitive listening environments.

Overall, middle-aged adults performed slightly poorer than young adults but showed performance patterns more similar to young than older adults. Word recognition in noise testing revealed that middle-aged adults exhibit greater binaural benefit at poorer signal-to-noise ratios compared to young adults but that this binaural benefit is lower than that obtained by older adults at all SBRs. Middle-aged adults showed a slight REA, similar in degree to that of young adults, in the free recall dichotic condition and larger ear advantages for the directed conditions compared to young adults. None of the middle-aged subjects exhibited individual performance patterns consistent with true binaural processing deficits. Nevertheless, middle-aged adults showed slightly-decreased performance relative to young adults and more variance in their performance compared to young adults. Despite the fact that the young and middle-aged groups had similar hearing sensitivity, the middle-aged adults exhibited a significantly-shallower slope in their performance function, thereby suggesting that they may lack the same efficiency that young adults possess in using improvements in the SBR to produce corresponding improvements in recognition performance. Further, there were some individuals in the middle-age category who did display unexpected patterns of performance – namely, poorer-than expected overall performance and relatively unequal performance between the monaural conditions. In sum, these results suggest that true deficits in binaural auditory processing may not present in middle age but that there are some indications that middle-aged adults may exhibit some age-related decline in processing of speech in competitive signals relative to young adults.

Clinical Implications and Future Research

The present study suggests that middle-aged adults perform best in difficult listening situations when listening binaurally as opposed to monaurally. When comparing these results to previously-collected data from young and older adults, middle-aged adults (with no more than a mild high-frequency symmetrical hearing loss) seem to perform more similarly to young adults than older adults. At the same time, however, the performance differences between middle-aged and young adults in tasks of binaural processing of speech in complex environments, though more subtle in nature, do propose some interesting clinical implications and questions. We know that the prevalence of hearing loss increases with age and therefore hearing loss is more common in older adults than young and middle-aged adults, but population studies reveal that a significant portion of middle-aged adults possess some degree of hearing loss (Agrawal et al., 2008). Often, these individuals report that understanding speech in background noise is one of their greatest challenges. Yet, there is a notable number of individuals in middle age who self-refer themselves for audiological services, reporting increased difficulty understanding speech in noise despite having normal to near-normal hearing sensitivity (see Helfer & Vargo, 2009; Leigh-Paffenroth & Elangovan, 2011).

As mentioned in the discussion, we know effective binaural processing is key to understanding degraded signals (i.e., speech in noise). By increasing our knowledge regarding binaural processing in complex environments across age groups, we can potentially provide more effective diagnostic and rehabilitative strategies. Though the use of technology (i.e., FM systems, loop systems) is often what we focus on in rehabilitative audiology, we may look to other areas that may be more cost-effective when faced with normal/near-normal hearing individuals who may not be candidates for amplification. In many cases, our treatment strategies for this population may instead involve using more specific and effective counseling strategies when interacting with a middle-aged adult patient who displays normal hearing sensitivity but presents with significant difficulty in noise. For these patients, providing information on compensatory strategies, environmental modifications, and speechreading could be empowering in improving their communication. Our rehabilitation protocol may also be as simple as verifying the individual's complaints by sharing information garnered from research on middle-aged adult binaural processing in complex environments.

In our current age where preventive medicine is obtaining widespread attention, we can further look into developing strategies that may be useful for a patient in proactively slowing and/or deterring age-related declines in auditory processing. Ross and colleagues (2007) discuss the potential future importance of this. Given that recent evidence suggests some aspects of binaural processing may begin to decline in mid-life, the area of auditory training as a compensatory and preventive tool may be an attractive area of future research. With today's widespread access of smartphones, tablets, and personal computers, these auditory training paradigms could be developed in a way that makes them attractive, user-friendly, and relevant to a widespread number of individuals.

For those middle-aged individuals who may be candidates or current users of amplification, bettering our understanding of performance patterns in this population may be beneficial in our treatment and validation of treatment. As the present study suggests, adults in mid-life display slightly poorer and more inter-individual variability in binaural processing than young adults. Being armed with this information, we may be inclined to use more thorough assessment and validation measures with this population, especially those who may be exhibiting a lack of success with their technology in complex listening environments. We may also be more inclined to try less traditional treatment measures, such as the use of monaural instead of binaural amplification in noise or the addition of an FM system for those who may be displaying decreased binaural benefit in noise (such as the 49-year-old individual discussed previously who displayed unexpected patterns of performance).

The present study may be beneficial in supporting past research and stimulating future study in age-related changes in binaural processing in complex environments. Our understanding of binaural processing in middle-aged adults is particularly in need of expansion due to the current lack of research in this area. Because most of the existing research focuses on young adults and older adults, much less is understood about what middle-age binaural processing looks like and how it compares to these other age groups. Additionally, an examination of binaural processing trends across middle-aged subgroups may also be an area of future research. For this experiment, 10 individuals were recruited for each decade age group (ten 30, 40, and 50 year-old participants). Expanding the number of subjects in each age group may be beneficial in allowing for a more thorough investigation of the differences within the middle-age group that the present study was unable to effectively explore, especially given the degree of variability among the middle-aged subjects.

The present study could also be adapted to include more difficult SBRs in the word recognition in noise task for the middle-aged adult group. The five SBRs used for young adults ranged from -4 to 12 dB, and those used for older adults ranged from 4 to 20 dB SBR. Because middle-aged adults were hypothesized to perform somewhere in-between these two groups, a range of 0 to 16 dB SBR was arbitrarily chosen. The middle-aged adults performed more similar to the young than the older adults, however, and the lowest SBR implemented for the middle-aged adults did not result in the same degree of difficulty to create the more complete performance function as seen in the young and older adults in Figure 2. Using more difficult SBRs may have resulted in a more comprehensive picture of middle-aged adult performance that the present study lacked, especially at the lower part of the performance function.

Another weakness of the present study was its restriction in using only right-handed individuals. Due to the higher variability exhibited among left-handed people for these particular listening tasks (Wilson & Leigh, 1996), handedness was controlled for using a questionnaire, and ambidextrous and left-handed people were excluded. The particular performance profiles of these individuals for these tasks are certainly less understood and would be a potentially interesting area of future research.

In addition, the decision to include individuals with up to a mild high-frequency hearing loss could be argued to be a weakness of the present study. The decision to extend inclusion criteria to those with no more than mild high-frequency losses was made based on the greater prevalence of this hearing loss in middle-aged adults and because the older adult age group possessed high-frequency hearing loss (of greater degree, on average). The young and middle-aged adults differed significantly in both the traditional pure-tone average (average of 500, 1000, 2000 Hz thresholds) and the high-frequency pure-tone average (average of 2000, 3000, and 4000 Hz). The effects of high-frequency hearing loss, even though mild in degree, must therefore be considered potential confounding factors in the differences in performance seen between young and middle-aged adults. Controlling for peripheral components like sensorineural hearing loss remains one of the difficulties in research that explores age-related central auditory decline. The present study could be altered to include only participants with normal hearing sensitivity.

In conclusion, the results of the current study are enlightening in that they provide further insight into the binaural processing of complex signals of middle-aged adults, an age group that is largely underrepresented in auditory research. Although we tend to focus on older adults when we consider age-related auditory change, a better understanding of the complete adult auditory lifespan may help us better serve audiology and – most importantly – our patients.

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